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Miniaturized Laser Spectroscopic CO Sensor for Industrial and Safety Applications

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Abstract

A miniaturized optical carbon-monoxide sensor based on tunable diode laser spectroscopy is presented and tested for various applications. It utilizes recently developed Vertical-Cavity Surface-Emitting Lasers (VCSELs) emitting at 2.3 µm as light source and the photodetector housing as integrated gas reference cell. Together with a wide/narrow spectral scan algorithm for wavelength stabilization, a compact, self-monitored and microcontroller-based sensor is realized. In contrast to conventional line-locking, the full wavelength scale of the spectral scans is inherently calibrated. The achieved sensing resolution (1 sigma) is 3 ppm for 1 second averaging.

Keywords: carbon-monoxide; laser spectroscopy; wavelength modulation spectroscopy; vertical-cavity surface-emitting laser;

1. Introduction

For industrial and safety applications e.g. exhaust-gas monitoring, fire detection and workplace monitoring, reliable and long term stable sensors are required. Usually, spectroscopic gas sensors have the lowest possible cross-sensitivity to other gases whereas tunable diode laser spectroscopy (TDLS) has the further advantage that sensors allow for self-monitoring to enable fail-save operation. These advantages predestine TDLS for sensors in safety applications or those where real-time and/or in-situ measurement is required.

Carbon monoxide (CO) is a toxic gas and affects human health whenever it is present in ambient air in high concentrations. Carbon monoxide poisoning is the most frequent cause of unintentional death at homes in the USA with a death toll of 500 persons per year [1]. The Threshold Limit Value (TLV) for CO at workplaces is 30 ppm, i.e. a permanent 30 ppm CO level is considered to be safe if a worker is exposed to it day after day during a working lifetime. Thus a CO sensor for safety applications must be able to resolve CO concentrations in the lower ppm range. Because the common particle-detection based fire detectors have unwanted cross-sensitivities to many substances like water vapor (especially in kitchens or bathrooms), hairspray or general dust, gas-sensor based fire

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detection seems to be an interesting approach for fire detection with reduced false alarm rates. Due to its absence in ambient air (<< 1 ppm) and its toxicity, CO is the prominent gas to be detected for gas sensor based fire detection [2]. A further application is the monitoring of CO in the exhaust of gas/oil furnaces for combustion optimization, which is very important for energy saving and reduction of pollutants.

2. Sensor Design

Here a miniaturized optical CO sensor based on TDLS is reported. It utilizes a 2.3 µm InP-based VCSEL [3] covering the first overtone CO gas absorption band, which is about 100 times stronger than the 1.5 µm range absorption band (second overtone) [4]. This enables ppm range sensing of CO by applying only 10 cm optical absorption path length with a sensor absorption resolution of 10^{-5} (@1 Hz). The schematic setup and image of the optical sensor with a reflective geometry is shown in Fig. 1 and Fig. 2, respectively.

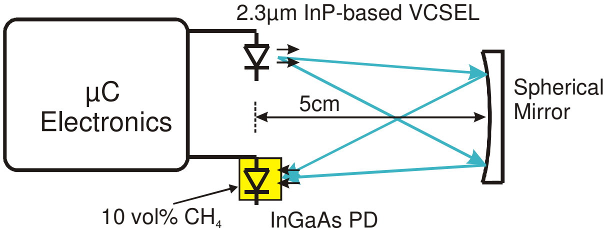

Fig. 1: Schematic setup of the optical CO sensor: the optical path length is 2 x 5 cm. The photodetector housing is filled with methane, which -like CO- also has absorption lines around 2.3 µm. It serves as reference gas for laser wavelength stabilization.

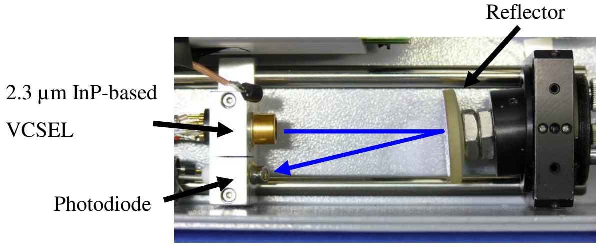

Fig. 2: Photograph of the optical cell of the CO sensor. The detector is tilted to minimize back reflection that cause unwanted interference effects ("fringes").

Because CO is a trace gas in ambient air, the natural absorption signal is below system noise in the scanned absorption spectrum. Conventionally, a separate reference cell containing the target gas and a second photodetector is used to control the emission wavelength of the laser to match the position of the CO line ("line locking"). By filling the reference gas methane in the housing of the photodetector of the main absorption cell, the sensor overcomes the disadvantage of the conventional optical cell – complex setup with many optical components – without loosing reliability. Since the reference gas is not the gas to be measured, no accuracy problems are expected when slight outdiffusion of the reference gas takes place. Compared to conventional edge emitting DFB lasers, VCSELs have a higher current-to-wavelength tuning range, which allows scanning of both adjacent methane absorption lines and the CO absorption line. The methane absorption lines around the CO absorption line are used as wavelength markers even when no CO is present. This "wavelength scale identification" is done in a wide spectrum scan (Fig. 3) each 6 s, whereas the CO concentration is determined in the more frequent narrow spectrum scans (Fig 4) each 100 ms. The continuous recalibration of the wavelength scale allows for compensation of the laser emission wavelength drift and changes of the linear and quadratic component of the tuning coefficient, which may happen if the laser ages. In the narrow scan, a linear (non-iterative) curve fit is done. Because of the known wavelength scale the reference spectrum of CO and methane can be computed analytically with the data from the HITRAN data base [5, 6]. The concentration of CO is an unknown linear parameter of the model for the measurement data and can be determined by just computing a simple scalar product. A microcontroller based electronics (10 cm × 10 cm size) serves for the signal processing, control and data evaluation.

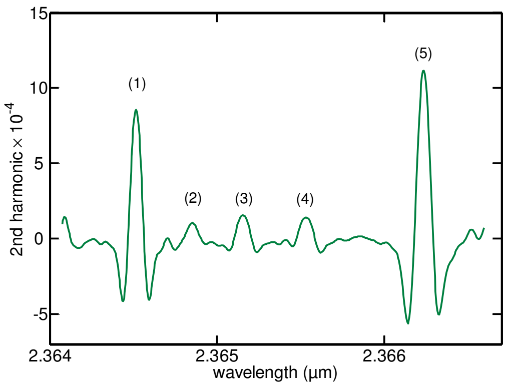

Fig. 3: Wide spectrum scan (duration: 512 ms, every 6 s): Second harmonic spectrum [7] of CH_4 and CO absorption lines normalized with the DC light power. The position of the methane lines (1), (5) and the larger one of (3) and (4) are detected and used for the determination of corresponding wavelength scale.

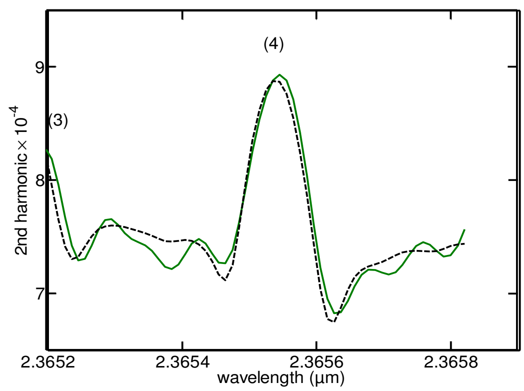

Fig. 4: Narrow spectrum scan (duration 64 × 1 ms, every 100 ms): second harmonic spectrum of CO and CH_4 absorption lines from a spectrum scan of 0.7 nm via current (solid curve), and the analytically computed and linearly curve-fitted reference curve (broken curve).

3. Test Results

The applicability of the sensor for different applications are tested by several real-condition tests: The one day measurement in a closed box with constant gas concentration for the Threshold Limit Value monitoring (Fig. 5). The fast time response of the sensor (100 ms) enables the observation of the CO peak in the exhaust gas of a gas furnace during on switching (Fig. 6).

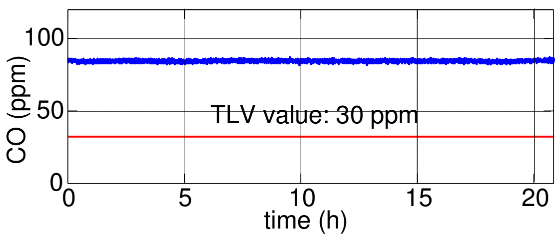

Fig. 5: One day measurement of CO concentration in a test gas chamber filled with 80 ppm CO. Detection of CO concentrations around the Threshold Limit Value (TLV) of 30 ppm can be reliably accomplished with an averaging time of 20 sec (1 sigma is 0.6 ppm)

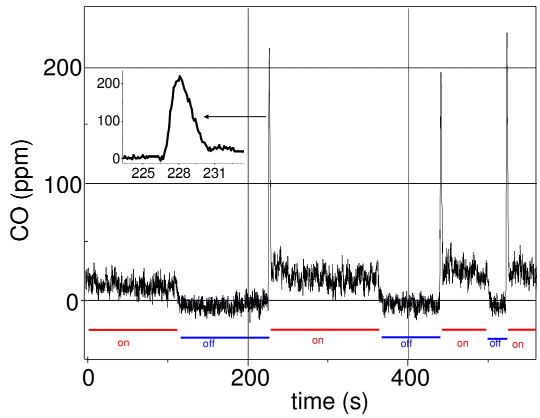

Fig. 6: Measured CO concentration in the exhaust of a gas furnace. The CO peak during on-switching of the furnace can be detected thanks to the sensor's fast response time of 100 ms.

CO measurements for fire detection (Fig. 7) showed that different types of fires (complete/incomplete) can be well detected and also distinguished in both absolute concentration and rate of increase. Gas sensor based fire detection directly measures the toxic gas components of a fire and exhibits significantly less cross-sensitivity compared to smoke or temperature based fire detectors, which is of special importance in cargo compartments of ships and planes.

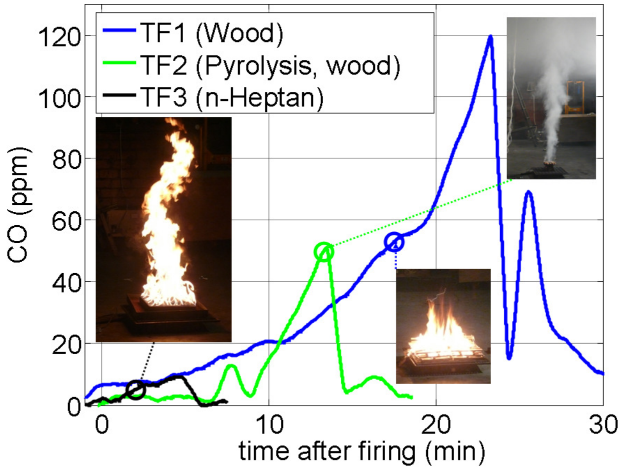

Fig. 7: CO concentrations measured in a room with different test fires. The concentration and also the rate of generation of created CO are very dependent on the type of fire. Burning of n-Heptane TF3 gives generally much less CO (10 ppm) than burning of wood, which has to be distinguished from pyrolysis TF2 (incomplete burning because of the lack of oxygen) and complete burning TF1. The sudden decay of the CO concentration is caused by ventilation of the room. The averaging time was set to 60 sec. Burning of n-Heptan cannot be detected with smoke detector because no smoke is generated in this case.

4. Conclusion

The first 2.3 µm VCSEL-based CO sensor with a miniaturized optical cell (~7 cm overall length feasible) is developed. The sensing resolution (one sigma) is 3 ppm at 1 Hz. It is more compact compared to conventional TDLS-based trace gas sensors, because the photodetector housing is used as reference cell for wavelength stabilization. By applying wide spectrum scans, permanent wavelength scale calibrating is realized. This enables self monitoring of sensor failures and aging of the sensor and sensor components, which is a significant advantage over other sensor principles. With the knowledge of the wavelength scale obtained from the wide scans, a linear curve fit algorithm (non-iterative) is implemented in narrow spectrum scans for CO concentration determination each 100 ms. Neither background or reference spectra measurements nor further calibration factors except for the line parameters from the HITRAN database are required.

Diverse tests in real conditions with the sensor show the applicability of the sensor for threshold limit monitoring, fire detection and combustion optimization in gas furnaces.

Acknowledgements

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